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Pion reabsorption in heavy-ion collisions interpreted in terms of the Δ capture process

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Abstract

We have measured energy-differential cross sections for π^0 production in $^{36}Ar+^{197}Au$ collisions at 95 MeV/u. From an analysis of spectral features due to pion final-state interactions we have estimated the cross section of the capture process $\Delta + N \rightarrow N + N$ in the center-of-mass energy range $\sqrt{s} \simeq 2.05$–2.25 GeV. Within the frame of BUU calculations, our results support the extension of the detailed-balance principle to broad-width resonances.

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It has been recognized that Δ(1232) isobars, as well as higher-lying nucleon resonances, play a major role in the dynamics of heavy-ion collisions in the few GeV/nucleon range [1,2]. Calculations suggest that these resonant states serve as an intermediate en-

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ergy storage and greatly enhance through multi-step processes the cross sections of high-p_t pion, as well as eta, kaon, and antiproton production at threshold. On the other hand, as mesons, and in particular pions, are subject to strong final-state interactions, which often involve resonance excitation, any interpretation of their propagation in the nuclear medium has to rely on an accurate knowledge of not only the resonance *production*, but also the *destruction* processes. However, elementary cross sections involving resonances in the initial channel are usually unknown and have to be estimated from the inverse process, if known, by applying the principle of detailed balance.

In case of the pion, the relevant processes are largely mediated by the Δ resonance through the elementary reaction $N+N \rightarrow N+\Delta$ (resonance creation) and its inverse $\Delta+N \rightarrow N+N$ (resonance capture). Whereas the first one is accessible to direct measurement, the cross section of the latter is obtained with the aid of detailed balance from the cross section $\sigma_{N+N\rightarrow N+\Delta}$ [3,4]:

$$\sigma_{\Delta+N\rightarrow N+N} = \frac{1}{N_f}\frac{p_f^2}{p_i^2}\,\sigma_{N+N\rightarrow\Delta+N} \tag{1}$$

where p_i, p_f, are the initial and final center-of-mass momenta, and N_f is the appropriate statistical factor. However, it has been shown [5,6] that, as these reactions involve a resonance of short lifetime, Eq. (1) has to be modified for the finite width of the resonance. Unfortunately, the experimental knowledge of the differential cross section $d\sigma/dM_{N+N\rightarrow\Delta+N}$ being still rather poor, one has to rely for the resonance mass distribution on theoretical models. Following the approximate ansatz of Wolf et al. [6] we write:

$$\sigma_{\Delta+N\rightarrow N+N} = \frac{1}{N_f}\frac{p_f^2}{p_i^2}\,\sigma_{N+N\rightarrow\Delta+N} \times \frac{1}{\int_{(M_N+M_\pi)^2}^{(\sqrt{s}-M_N)^2} F(M^2)\,dM^2} \tag{2}$$

where $\sqrt{s}$ is the energy available in the $\Delta+N$ system and $F(M^2)$ represents the Δ mass distribution. This so-called 'extended detailed-balance principle' needs to be verified, which can be done through an experimental determination of $\sigma_{\Delta+N\rightarrow N+N}$ and by comparison with the known cross section $\sigma_{N+N\rightarrow\Delta+N}$ [7].

In this Letter we present an analysis of π^0 kinetic-energy spectra measured in heavy-ion collisions at 95 MeV/u, i.e. a bombarding energy where most of the data are concentrated in the region below the Δ resonance at $E_{\rm kin}(\pi) \simeq 200$ MeV. From the shape of the spectra, strongly affected by the pion final-state interactions in the nuclear medium, we have extracted a pion absorption cross section $\sigma_{\rm abs}$. Within the standard assumptions of the Boltzmann-Uehling-Uhlenbeck (BUU) transport theory, i.e. supposing in particular that $\sigma_{\rm abs}$ encompasses both the $\pi+N\rightarrow\Delta$ and $\Delta+N \rightarrow N+N$ processes, we have obtained an experimental estimate of the elementary cross section $\sigma_{\Delta+N\rightarrow N+N}$ for center-of-mass energies $\sqrt{s} \simeq$ 2050–2250 MeV, allowing for a test of the extensions applied to the detailed-balance principle within that framework.

In a measurement performed at GANIL, gold targets of 20 mg/cm^2 were irradiated with a 95 MeV/u ^{36}Ar beam. Photons were registered in 320 BaF_2 detectors from the two-arm photon spectrometer TAPS [8], arranged in 5 blocks of 64 scintillators each and all equipped with individual plastic charged-particle veto detectors. Neutral pions were detected with an efficiency of 1.6%, as determined from a GEANT simulation of the detector response, and identified through an invariant-mass analysis of 2-photon events, yielding a FWHM resolution of the π^0 peak of 13%. More details on the setup and the data reduction have been presented previously [9,10]. From our data we deduce an inclusive cross section for π^0 production of $\sigma_{\pi^0} = 1.16 \pm 0.12$ mbarn, in excellent concordance with systematics [11].

In a former paper [9] we showed that the π^0 polar and azimuthal angular distributions can be described for the reaction system studied here in terms of a mid-rapidity source, in combination with large pion shadowing effects. This result strongly supports the picture of subthreshold pion generation in nucleon-nucleon collisions in the very first stage of the reaction, in line with BUU transport calculations [11]. In a BUU calculation where pion production is treated perturbatively, with elementary cross sections taken from [7], we find a primordial pion spectrum, i.e. the one prior to all final-state interactions, which can be well approximated by a Maxwellian distribution of the form $E_{\rm kin}\cdot\exp(-E_{\rm kin}/T_0)$, with $T_0 = 28$ MeV at 95 MeV/u. The BUU code used has been shown [12] to reproduce very well the shape of the concurrently measured *pn* bremsstrahlung spectrum [10], which offers a direct check of its predictive power. The present BUU result suggests that, for inclusive pion events at least, the folding of the nucleon Fermi momenta with the elementary pion production cross section results in a very close to thermal phase-space occupancy. Deviations from the pure Maxwellian shape are expected and are presumed to hold information on the pion rescattering and reabsorption processes [13]. For an interpretation of these effects, the advantage of subthreshold pions is twofold: (1) they are produced in the very first phase of the collision, i.e. in a well-defined overlap volume, and (2) they interact mostly with rather cold spectator matter, as they propagate faster than the collision itself proceeds.

To describe the π^0 final-state interactions, we made use of Monte Carlo calculations on the basis of a model [9,13] in which the pions are emitted uniformly from a mid-rapidity source formed by the overlap region of the two colliding nuclei and propagated until they are absorbed or leave the reaction system. This semi-classical approach is justified [14], as for $E_{\rm kin}(\pi) \gg 50$ MeV the de Broglie wave length of the pion is smaller than the typical inter-nucleon distance. We have however extended the above scheme as follows: for the pion source, the Maxwellian energy distribution predicted by BUU is put in ad hoc, as well as an *NN* cm intrinsic angular distribution of the type $d\sigma/d\Omega \propto 1 + A_2 P_2(\cos\theta)$, where $A_2 = 0.8$ reproduces the measured π^0 angular distributions. Pion absorption is characterized by a momentum-dependent absorption length $\lambda_{\rm abs}(p)$, to be extracted from the data, and pion rescattering is calculated from the isospin-averaged known πN scattering cross sections [15,16], reduced for Pauli blocking in the nuclear medium. Including rescattering has three effects: (1) it slightly decreases the apparent temperature of the pion source, namely from $T_0 = 28$ to $T = 26$ MeV, (2) it smears out angular anisotropies, requiring an intrinsic $A_2 = 0.8$, instead of the 0.4 found in [9], to reproduce the measured angular distributions and (3) it increases the mean path $<D>$, that pions travel in nuclear matter before they escape, with respect to the straight-line approximation by $\simeq$5% at threshold and up to 25% in the Δ resonance region. Beyond elastic scattering, charge-exchange processes give a sizeable contribution to the pion total scattering cross section, but, as the $\pi^0 \rightleftharpoons \pi^\pm$ transmutations nearly cancel, they have only little net effect on the final π^0 yield.

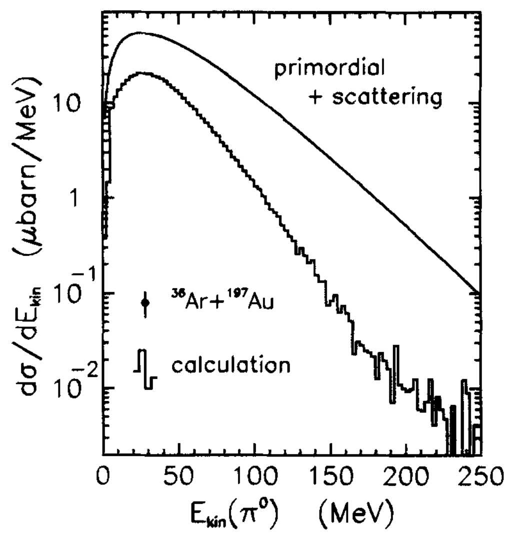

Fig. 1. Angle-integrated π^0 kinetic-energy spectrum in the *NN* cm system (symbols), corrected for the detector acceptance and response. The solid line is a $E_{\rm kin} \cdot \exp(-E_{\rm kin}/T)$ distribution, with $T = 26$ MeV, representing the primordial pions after rescattering (see text for details) and the histogram is the corresponding spectrum calculated including also reabsorption.

The measured π^0 angle-integrated kinetic-energy spectrum, transformed into the *NN* cm frame, is shown in Fig. 1. In contrast to rescattering, reabsorption reduces the observable pion yield. Therefore, the ratio of the measured yield and the calculated one, including rescattering effects, i.e. with $T = 26$ MeV, gives the pion escape factor $f_{\rm esc}$ as function of energy (or momentum). As in Ref. [13], we obtain the momentum-dependent π^0 absorption length shown in Fig. 2a by setting $f_{\rm esc}(p) = \exp[-<D>(p)/\lambda_{\rm abs}(p)]$, where $<D>(p)$ is taken from our simulation. Here, the absolute normalization of the primary pion distribution has been chosen such that the energy-averaged absorption length is $<\lambda_{\rm abs}> = 5.7$ fm, compatible with our previous findings [9,13]. As a consistency check, we compare in Fig. 1 the measured and calculated energy spectra, where the latter are averaged over impact parameter, and include now both rescattering *and* reabsorption effects. Theoretical calculations of $\lambda_{\rm abs}(p)$ based on pion-nucleus optical potentials [17,18] agree in magnitude and momentum dependence with the present result, lending further confidence to our analysis [see Fig. 2a]. They allow

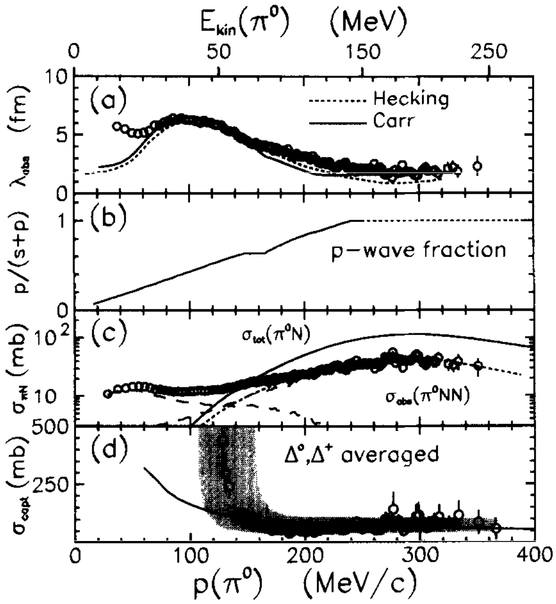

Fig. 2. (a) π^0 absorption length as function of the pion momentum. Pion-nucleus optical-model calculations done for $\rho_0 = 0.17\ \mathrm{fm}^{-3}$ [17,18] are also shown as lines. (b) Calculated p-wave fraction of the π^0 absorption. (c) In-medium π^0 total (σ_{tot}) and absorption (σ_{abs}) cross sections. The long-dashed lines represent an optical-model s-wave/p-wave decomposition, i.e. σ^s_{abs} and σ^p_{abs}, and the short-dashed curve is a Breit-Wigner fit to σ^p_{abs}. (d) Δ capture cross section extracted from the data, shown together with a calculation according to Eq. (2), smeared with the nucleon Fermi momenta. Error bars are statistical, systematic errors of the analysis are indicated by the shaded band.

in addition to estimate the p-wave fraction of the absorption [Fig. 2b], i.e. to decompose it into s-wave and p-wave contributions. From $\lambda_{abs}(p)$ we have then obtained in a next step the cross section σ_{abs} for π^0 absorption at normal nuclear density ρ_0, shown in Fig. 2c, by putting $\sigma_{abs}(p) = 1/[\lambda_{abs}(p) \cdot <\rho>^2/\rho_0]$, with a mean density of the system, dynamically calculated by BUU and averaged over impact parameter, of $<\rho> = 0.15\ \mathrm{fm}^{-3}$. Since the optical-model calculations imply that σ_{abs} is dominated at low pion momenta by s-wave terms and at high momenta by p-wave terms, i.e. the Δ-resonance, we have used the calculated p-wave fraction to decompose the cross section, as shown in Fig. 2c, into σ^s_{abs} and σ^p_{abs}. The resulting p-wave contribution to π^0 absorption can be fitted reasonably well with a Breit-Wigner curve of width $\Gamma_{abs} \simeq 170$ MeV at resonance, i.e. sizably larger than the width of the free Δ ($\Gamma = 120$ MeV), in accord with microscopic calculations [19].

Finally, within our semi-classical frame work, an estimate of $\sigma_{\Delta+N\to N+N}$ has been obtained in the following way: when a Δ is excited on a nucleon in the process $\pi + N \to \Delta$, it can either decay with a decay length $\lambda_{decay} = \beta_\Delta\gamma_\Delta\hbar c/[\Gamma(M) \cdot B_P]$ or be captured on a second nucleon with a capture length $\lambda_{capt}(s)$ [3,20]; here $\Gamma(M)$ is the mass-dependent width of the Δ and B_P is a blocking factor taking into account the increase in lifetime of the Δ due to partial Pauli blocking of its decay. Unlike the latter, the capture of the Δ is however only weakly Pauli-blocked [3]. If the excitation process happens on a free nucleon, the mass M of the Δ equals the total cm energy $\sqrt{s}$ and is kinematically related to the momentum of the incident pion. In the nuclear medium, however, $\sqrt{s}$ is smeared by the Fermi motion of the nucleon, spoiling this simple relation. We define now a Δ capture probability which, on the one hand, is related to the above quantities by $P_{capt} = \lambda_{decay}/(\lambda_{decay} + \lambda_{capt})$ [3] and, on the other hand, can be obtained experimentally from the ratio of the measured π^0 absorption cross section σ^p_{abs} and the Fermi-smeared total $\pi^0 N$ cross section σ_{tot}, i.e. $\sigma^p_{abs} = P_{capt} \cdot \sigma_{tot}$. For the latter we take the isospin average of the free cross sections of $\pi^+ N$ and $\pi^- N$ scattering [16], dominated by the Δ resonance for pion momenta up to 500 MeV/c [see also Fig 2c]. As mentioned above, σ_{tot} comprises elastic and charge-exchange scattering, but as both neutral and charged pions transmute into one-another, in first order, the total number of π^0 is conserved. In the Δ-resonance region, we find $P_{capt} \simeq 0.35$. Next, from the experimental value of P_{capt} and the calculated λ_{decay}, with $\Gamma(M)$ taken from Ref. [21] and B_P from our BUU calculation, the capture length λ_{capt} has been evaluated as function of the pion momentum. In a last step, from λ_{capt} we have obtained the cross section for Δ capture, shown in Fig. 2d, with $\sigma_{capt} = 1/(\lambda_{capt} \cdot \rho_0)$. We have performed a systematic investigation of the sensitivity of this result to the various parameters entering our analysis. The shaded band in Fig. 2d encompasses $\pm 15\%$ variations of T_0, $<\rho>$, $<\lambda_{abs}>$ and the p-wave fraction used to extract σ_{capt}. As changes of these input parameters directly affect the magnitude of the calculated absorption cross section, and its decomposition into s-wave and p-wave parts, the corresponding systematic errors are mainly ordinate errors. Only $<\rho>$ has, via the Fermi smearing, a repercussion on the abscissa corresponding to σ_{tot}. The divergent behaviour of σ_{cap}, as well as of its systematic errors with decreasing pion momentum is simply due to the fact that $P_{capt} \rightarrow 1$ when $\sigma^{p}_{abs} \rightarrow \sigma_{tot}$. Finally, in the present analysis, more complicated processes involving three-nucleon absorption [22,23] have been neglected altogether.

Our experimental result for σ_{capt} is compared in Fig. 2d with a detailed-balance calculation [6] done with Fermi-smeared kinematics, assuming isospin symmetry and neglecting Coulomb interactions between the Δ isobar and the nucleon. As we deal here with neutral pions, in first order, only processes involving the Δ^+ and Δ^0 states have to be considered. One sees that the agreement with the data is quite good, except for $p(\pi) < 140$ MeV/c, which might be attributed to the strong increase of our systematic errors at low momenta. In a final analysis step, we have unfolded σ_{capt} for Fermi smearing by multiplying it with the ratio of the theoretical cross sections, calculated once on the free nucleon and once in-medium. The resulting estimate of the elementary cross section $\sigma_{\Delta+N\rightarrow N+N}$, i.e. the one for free ΔN collisions, is shown in Fig. 3 as function of the cm energy in the range $\sqrt{s} = 2050$–2250 MeV. It clearly appears that the correction to Eq. (1) for the finite width of the Δ, introduced in Eq. (2), is required in order to reproduce the steep increase observed in the data at low $\sqrt{s}$. A calculation based on a different, but still not exact ansatz for the mass dependence $F(M^2)$ entering Eq. (2), proposed initially by Danielewicz and Bertsch [5], predicts a smaller cross section, although, given our experimental uncertainties, as well as the definite model-dependence of the analysis, a clear-cut discrimination between the two approaches seems, at present, still difficult.

In summary, we have studied inclusive π^0 production in the reaction ^{36}Ar+^{197}Au at 95 MeV/u. The measured π^0 kinetic-energy spectra are described in terms of a mid-rapidity pion source, in combination with strong rescattering and reabsorption effects. From an analysis of the latter and within the scope of the BUU model, we deduce cross sections for π^0 absorption in nuclear bulk matter, as well as an estimate of the cross section of the capture process $\Delta + N \rightarrow N + N$ at low $\sqrt{s}$. A comparison of our result with calculations gives clear support to the standard schemes applied to extend the detailed-balance principle to finite-width resonances, and therefore allows for an important consistency check of microscopic transport theories describing hadronic matter dynamics and particle production in the 100 MeV/u to few GeV/u range.

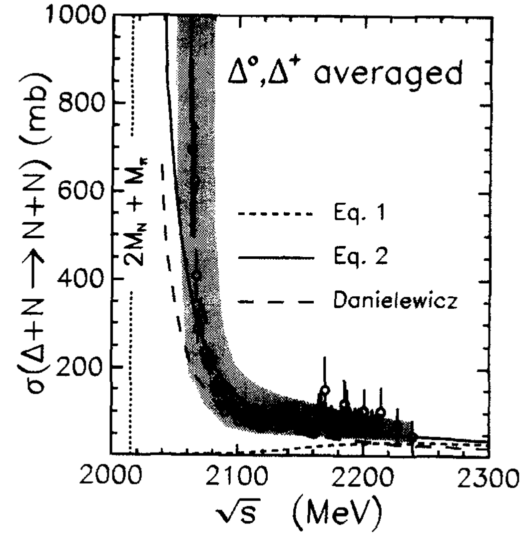

Fig. 3. Elementary Δ capture cross section as function of the ΔN cm energy $\sqrt{s}$. The shaded band corresponds to systematic errors. Lines are detailed-balance calculations according to Eq. (1) (short-dashed), Eq. (2), i.e. Wolf et al. [6] (solid), and to Danielewicz and Bertsch [5] (long-dashed). The absolute threshold at $2M_N + M_\pi$ is also indicated.

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References

[1] R. Stock, Phys. Rep. 135 (1986) 259;
H. Stöcker and W. Greiner, Phys. Rep. 137 (1986) 277.
[2] V. Metag, Prog. Part. Nucl. Phys. 30 (1993) 75.
[3] Z. Fraenkel, Phys. Rev. 130 (1963) 2407.
[4] G.F. Bertsch and S. Das Gupta, Phys. Rep. 160 (1988) 189.

[5] P. Danielewicz and G.F. Bertsch, Nucl. Phys. A 533 (1991) 712.
[6] Gy. Wolf, W. Cassing and U. Mosel, Nucl. Phys. A 545 (1992) 139c; A 552 (1993) 549.
[7] B.J. VerWest and R.A. Arndt, Phys. Rev. C 25 (1982) 1979.
[8] R. Novotny et al., IEEE Trans. Nucl. Sci. 38 (1991) 379.
[9] A. Schubert et al., Phys. Lett. B 328 (1994) 10.
[10] A. Schubert et al., Phys. Rev. Lett. 72 (1994) 1608.
[11] W. Cassing, V. Metag, U. Mosel and K. Niita, Phys. Rep. 188 (1990) 365.
[12] R. Holzmann et al., in: Proceedings of the 7th International Conference on Nuclear Reaction Mechanisms, Varenna, June 6-11, 1994, edited by E. Gadioli.
[13] R.S. Mayer et al., Phys. Rev. Lett. 70 (1993) 904.
[14] L.L. Salcedo et al., Nucl. Phys. A 484 (1988) 557.
[15] Landolt-Börnstein, Elastic and Charge-Exchange Scattering of Elementary Particles, Vol. I/9b2 (Springer Verlag, Berlin, 1983).
[16] Review of Particle Properties, L. Montanet et al., Phys. Rev. D 50 (1994) 1173.
[17] P. Hecking, Phys. Lett. B 103 (1981) 401.
[18] R. Mehrem, H. Radi and J.O. Rasmussen, Phys. Rev. C 30 (1984) 301.
[19] E. Oset and L.L. Salcedo, Nucl. Phys. A 468 (1987) 631.
[20] J.N. Ginocchio, Phys. Rev. C 17 (1978) 195.
[21] Y. Kitazoe et al., Phys. Lett. B 166 (1986) 35.
[22] D. Ashery and J.P. Schiffer, Annu. Rev. Nucl. Part. Sci. 36 (1986) 207.
[23] T. Alteholz et al., Phys. Rev. Lett. 73 (1994) 1336.